

An experimental analysis of the optical, thermal and power to weight performance of plastic and glass optics with AR coatings for embedded CPV windows



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ABSTRACT

A low concentrator photovoltaic is presented and the optical losses within a double glazed window assembly are described. The use of plastic instead of glass is analyzed for its reduced weight and hence greater power to weight ratios. Although the transmittance of glass is higher, the power to weight ratio of the plastic devices was almost double that of the glass counterparts and even higher than the original non concentrating silicon cell. The plastic Topas material was found to be the best performing material overall. Crystal Clear, a plastic resin, had a higher average transmittance but had a lower optical efficiency due to the cold cast manufacturing process in comparison to injection moulding of the other materials. This proves the importance of considering both the materials and their associated manufacturing quality.

External quantum efficiencies, optical properties, silicon cell temperatures and performance is analyzed for concentrating photovoltaic devices made of varying optical materials. The measurement methods for optical analysis are given in an attempt to separate the optical losses experimentally. The Silicon cells were found to gain higher temperatures due to the insulating plastic optics in comparison to glass but these effects are eliminated during vertical window orientation where instead the encapsulate dominates the insulation of the cell. The results presented here prove plastic optics to be a worthwhile alternative to glass for use in low concentration photovoltaic systems and have the significant effect of reversing the weight disadvantage concentrator photovoltaic technology has compared to standard flat plate solar panels.

1. Introduction

Concentrator photovoltaic (CPV) systems are an expanding research topic with various applications and benefits. The demand for cleaner energy from synergistic technology and infrastructure is increasing and poses many promising benefits [1]. At present, most domestic photovoltaic (PV) technology is attached on top of roofs and facades as opposed to building integrated. The design of such embedded systems however should be aesthetically pleasing as well as high performing to meet domestic energy demand. Concentrator Photovoltaics (CPV) are an option for expanding the flexibility and variety of integrated PV

design as well as achieving higher energy conversion efficiencies. Recent market research has also suggested that for CPV to compete with standard flat plate PV, niche applications such as building integration, using embedded systems, need to be developed [2,3] which can take advantage of the limited installation space.

One of the constraints of concentrator photovoltaic technology is the associated weight of systems [4–6] which can hinder applications in buildings and vehicles. Glass, although a very reliable and high performing material in terms of optical efficiency, adds weight to devices when used for the primary or secondary optic. Plastics are an alternative material with lower weight but also lower transmittance values

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[7]. For photovoltaic technology embedded into building facets and windows, plastic materials are an evident alternative to reducing weight, cost and handling difficulty [8]. The development of plastic optics will also be beneficial to the design and manufacturing of luminescent solar concentrators (LSC) and similar nano-fluid type CPV technologies where flexible materials are commonly used [9,10]. Plastics also typically transmit poorly in the infrared region of the solar spectrum which could be beneficial as a filtering step when coupling with silicon solar cells. Silicon solar cells of working range 300nm–1100nm will be used in these experiments and any incident wavelengths outside this range will be converted into unwanted heat energy and contribute to a decrease in the solar cells converting efficiency.

The endurance and reliability of concentrator photovoltaic technology in general requires further research and even more so for the cases of alternative materials and the implications for building integrated technology [11,12]. Here we present a low concentration photovoltaic for novel applications as a window where some light passes through for indoor daylighting and some is concentrated to a silicon solar cell for electricity generation. In this way, any 'light loss' due to the optics of the CPV system embedded within the window, will contribute to the daylighting of the inner room, and hence be useful. This is a unique method of taking full advantage of CPV technology including even the optical scattering 'losses'. We compare the performance of optics made of glass, Topas (Zeonex), Crystal Clear, and Polycarbonate as well as the effect of antireflective (AR) coatings. Considerations of the encapsulation material (Sylgard 184 in this case) which would be used to join the optic to the cell are also included. This is a comprehensive study including practical thermal and material effects on the solar cell performance and power to weight ratio. The performance of different manufacturing methods, injection moulded and cold cast, for CPV optics is also compared. The results given here may directly aid the commercialization and upscaling of window CPV technology, namely the optical materials choice for manufacturing.

The low concentration optic under study (see Fig. 1a) is a crossed compound concentrator (CCPC), previously optimized by Baig et al. [1,13]. and Sellami et al. [14]. The full system design consists of an array of these optics sandwiched between two glass panes and sealed in a similar fashion and with the same thickness to that of a double-glazed window (Fig. 1a). The CCPC has a geometric concentration ratio of 3.6 X and an acceptance angle (when optical efficiency is > 90% of normal incidence maximum) of 35° [13].

2. Optical losses, material properties and measurement methods

In optical systems and photovoltaics there are many losses. Each optical layer will contribute its own portion of inefficiencies and inaccuracies as shown in Fig. 1a. The magnitude of these losses depends on the incident light, specifically its wavelength and angle of incidence, as well as the materials chosen and their associated properties. The most commonly considered properties are refractive index and transmittance however the surface quality and thermal conductivity is also of importance, both of which proven in this study. Antireflective Coatings can also be incorporated to reduce the amount of Fresnel reflection (see Fig. 1a) when light is incident on a medium interface but must suit the medium interface (e.g. air to glass). Most AR coatings work by easing the transition from one refractive index to another, increasing or decreasing the refractive index in steps or as an effective gradient.

The manufacturability of each component and the resultant optical finish can dominate the other attributes of a material when it comes to final performance. The surface roughness of the optic can result in light failing Total Internal Reflection (TIR) and refracting out of the optics side walls as suggested in Fig. 1a or scattering within the optic but in the wrong direction. This is a crucial detail when designing low concentration optics such as the CPC since the optimized acceptance angle

will rely on the refractive index, TIR critical angle, geometry limitations, and assumed surface qualities. Here we have tested injection moulded optics but also cold cast optics made with crystal clear. Injection moulding is considered one of the most efficient methods to manufacture a high number of high quality optics and is the most cost effective for scaled up industrial productions of optics. Cold cast optics can be made in house and although the moulds can still be expensive, they are typically cheaper than injection moulds and a non-specialist can mix and pour the desired resin into the cast, seal and clamp the cast for the required setting time. This means no expensive injection moulding equipment needs bought or the facilities and expertise hired but casting can take up to 48 h per mould. Hence, this method is typically used for prototyping productions. The measurement methods shown in Fig. 1b and d are typical for the analysis of concentrating photovoltaic (CPV) systems along with Monte Carlo ray trace simulations for design optimisation (which has been done previously [13]). However, due to the size of the CCPC optics used (dimensions given in Fig. 1a), the spectrophotometer measurement will give not simply the straight through transmittance but also include any light loss at the CCPC side walls and incomplete refraction losses at the exit aperture (Fig. 1b). In device form, with the solar cell attached, this 'incomplete exiting' is replaced with the smaller cell reflection losses. Hence we have introduced the use of the External Quantum Efficiency without (Fig. 2a) and with (Figs. 1c and 3f) the optic attached which can be compared to give the most accurate transmittance through the optic. EQE testing of the silicon cell without any optics is of course required to be undertaken first.

It is well studied that with increasing cell temperature the solar cell efficiency, open circuit voltage and overall power output will decrease as shown in Fig. 2b for the silicon cell used here. As well as this, there is a spectra drift for the External Quantum Efficiency (EQE) with increasing temperatures as shown in Fig. 2a.

The External Quantum Efficiency (EQE) of the solar cells (Fig. 2a) can be seen to be over 90% from around 450–900nm. When the temperature of the cell increases, the EQE of the cell shifts very slightly towards the infrared region [15,16], from close ups (i) and (ii) you can see that at around 380nm the cell gives a higher EQE at colder temperatures but at 1100nm the spread is more noticeable but the EQE is higher at higher temperatures. For temperatures up to 60°C there is negligible difference in the EQE range, if anything the EQE is arguably improved at the higher temperatures. Fig. 2b shows the decrease in solar cell open circuit voltage, power and efficiency up to 55°C where afterwards the solar cell internal temperatures are too high to transport the current from full illumination and hence breaks down as shown in Fig. 2b for 57°C. This is a relatively low cell temperature to exhibit such break down. The temperature was measured at the back of the cell using a thermocouple directly in contact with the metal back of the cell (as shown in Fig. 1d) such that the surface temperature of the cell is expected to be slightly higher than the measured values. Furthermore, the cell's surface will have an uneven temperature profile with peaks matching higher concentration points due to the irradiance distribution using this type of optic. The irradiance distribution is reported in detail by Baig et al. [1,13]. and Sellami et al. [14]. who suggested the non-uniformity to be negligible for low concentration optics but perhaps for the insulating plastic optics and the non-optimized silicon cells used this has a more significant effect. The cells were originally designed for 1 sun concentration and uniform irradiance exposure. These cells have been cut to 1cm by 1cm sized with the necessary metallization pattern altered for connection. The altered metallization pattern included closer spaced lines to draw the increased current away but this may not have been enough to cope with the non-uniform irradiance and temperature distribution. The peak concentrated irradiance points on the cell will have higher internal cell resistances and temperatures but are not located at the centre of the cell but towards the corners [13] as well as being very localised. Cells designed specifically for this level of concentration would be expected to continue to perform at higher

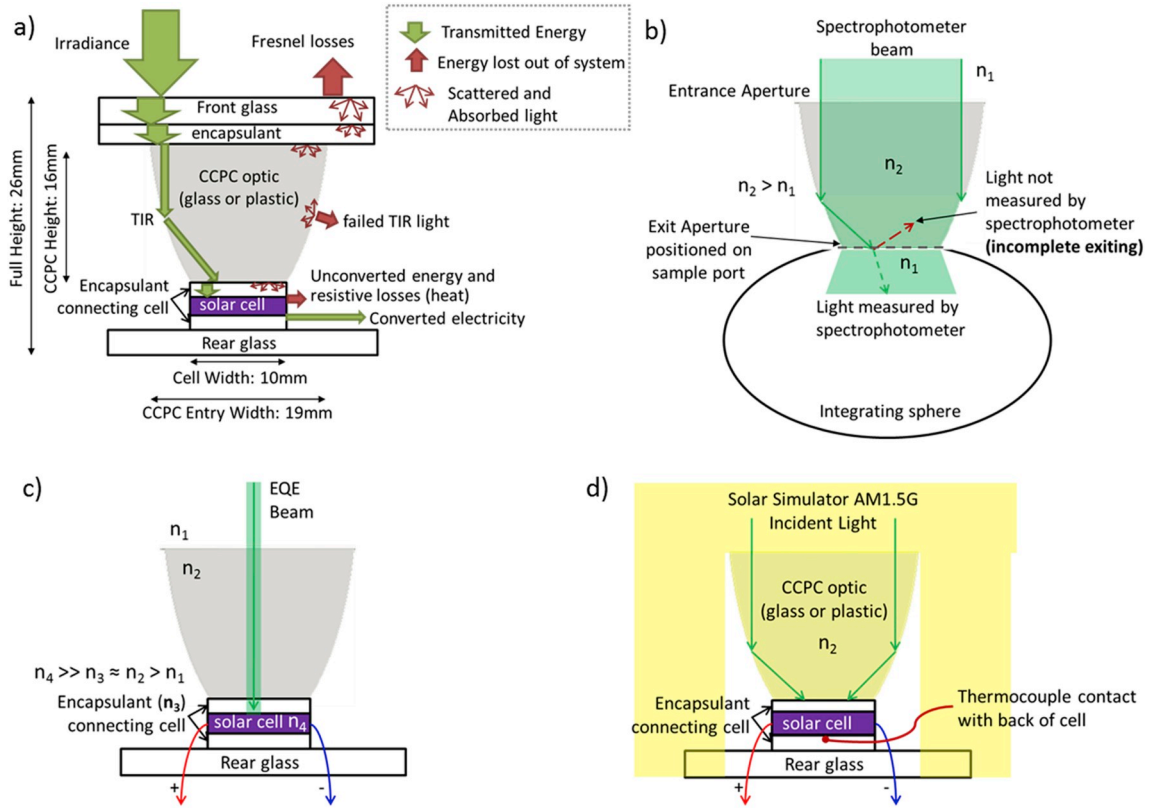


Fig. 1. (a) Diagram of proposed embedded window system with double glazing glass sandwiching CCPC optic and solar cell within. Energy progression and losses through the system are marked. (b) Spectrophotometer set up to measure the optical efficiency of the optic but with incomplete exiting as the light must exit from a high refractive index to a low refractive index. (c) Effective External Quantum Efficiency measurement set up which accounts for absorption losses, refractive losses and cell reflection within the silicon cells response range (300–1100nm). (d) Solar simulator set up for measuring I–V output and temperature of the Silicon under increasing exposure times.

temperatures and would likely produce even more enhanced results than obtained in this prototyping study [17]. The Silicon cell under study loses ~2% efficiency due to operating at an increased temperature of 45°C. This equates to roughly a loss of ~1% per 10°C increase above standard operating temperature (25°C). Even though the short circuit current increases with increased temperature, the open circuit voltage decreases [18,19,20], lowering the efficiency. How these behaviours manifest whilst also under increased irradiance due to the optics concentrations and different irradiance distribution across the

cell [1] is another interesting consideration. An increase in irradiance will increase the open circuit voltage and cell efficiency but with only a smaller logarithmical relationship in comparison to the temperature decrease linear dependency [18,19,20]. Like most cells, the cells utilised here will have an optimum performance within a certain irradiance and temperature range [17], this is however unknown for these cells due to their customisation.

Although high cell temperatures may not be expected when utilising low concentration photovoltaics (LCPV) such as this (3.6x geometric

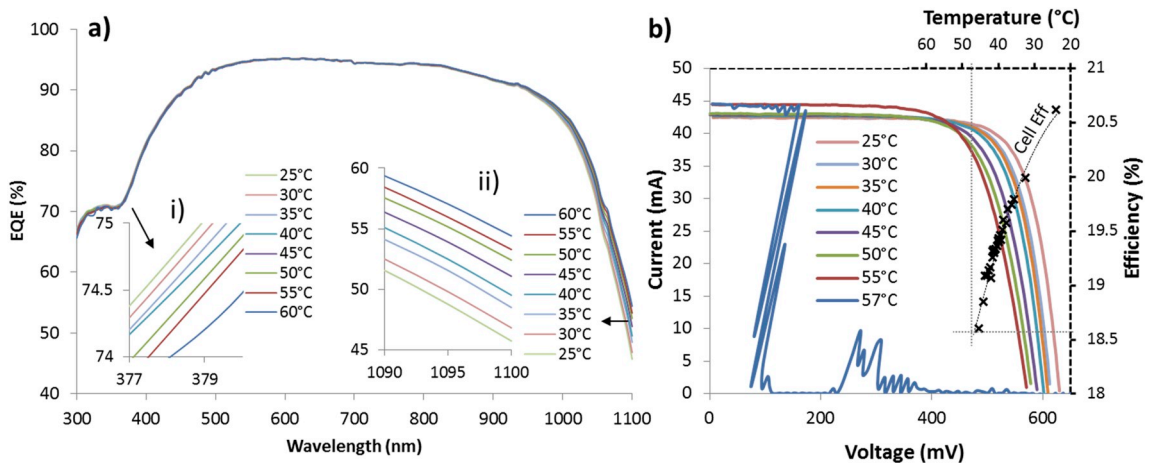


Fig. 2. a) External Quantum Efficiency (EQE) and b) I–V traces of the Silicon solar cell at increased temperatures including cell efficiency vs. temperature. a. (i) Close up of results at low end of spectrum. a. (ii) Close up of Results at high end of spectrum. (b) I–V traces of Silicon solar cell at increased working temperatures where the cell efficiency is also plotted against temperature overlaid on the top right of the graph

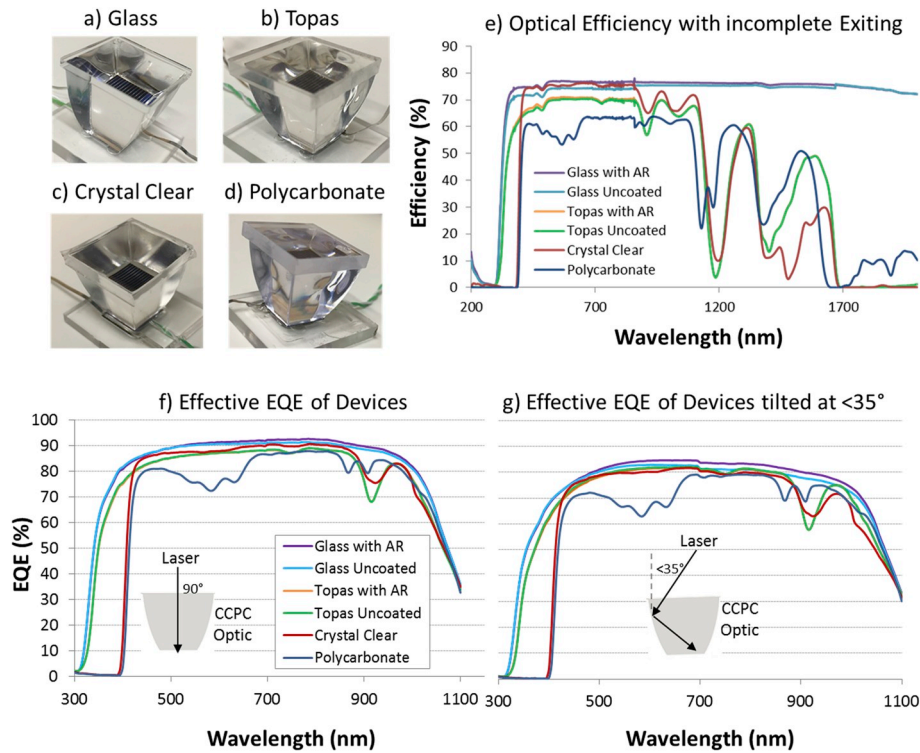


Fig. 3. (a-d) images of CCPC optics made from different optical materials. (e) Transmittance spectra measured through each CCPC optic made of the different optical materials. Glass and Topas optics also coated with a single AR layer of magnesium fluoride. (f) Normal incidence effective EQE and (g) angled incidence effective EQE.

Table 1

Optical Material Properties including Thermal Conductivity, Weight and Refractive index. The weight is of an individual CCPC optic made of the specified material.

Material	Thermal Conductivity (W/mK)	CCPC Weight (g)	Refractive Index
Glass (Crown: CDGM -K)	0.96-1.05	10.41	1.523
Topas (Polyolefin/Zenonx: COC Polymer)	0.12-0.15	4.94	1.525
Crystal Clear (Urethane Resin)	~0.2	5.62	1.499
Polycarbonate (PC)	~0.19	5.58	1.587
Sylgard 184 Encapsulate (Silicone Elastomer)	~0.2	n/a	1.423

concentration ratio CCPC) the attachment of optics upon the solar cells, especially plastic ones, will have an insulating effect upon the cell. The thermal conductivity of the materials used here are given in Table 1 and as expected the plastic materials have a significantly lower thermal conductivity than glass and hence will contribute to the increased heating of the solar cell.

3. The transmittance and effective External Quantum Efficiency

The different cold cast and injection moulded optics are shown in Fig. 3a. Visually speaking, the glass optic (Fig. 3a) looks the clearest and smoothest in terms of optical surface qualities. The Topas and Polycarbonate optics (Fig. 3b and d) have some shrinkage flaws on the side walls of the optics. This is a manufacturing flaw as these optics were made by hiring an injection moulding company's equipment and using our own materials. The inner volume cools much slower than the outer surface causing a warping and shrinkage deformation. This can be minimised by taking the parts and putting them instantly into an oven to cool them gradually (this was carried out for the optics used). In a scaled industrial process alehr (a conveyor belt system used for production lines) would carry the moulds through gradually cooler temperatures to eliminate these flaws. This was one reason for carrying out the effective EQE measurements shown in Fig. 3f as the equipment laser will not hit the side walls (as in the spectrophotometer displayed in Fig. 1b) and only be affected by the materials absorption and small

Fresnel losses on the surface entrance (Fig. 1c). The transmittance measurements shown in Fig. 3e involves are larger measurement beam area (> 10mm) which could not be guaranteed to not also hit the side walls of the CPC and hence could be showing a combination of the absorption losses, Fresnel losses and slope error defects (incomplete TIR) as shown in Fig. 1a. By testing the effective EQE, the absorption losses could be isolated from any moulding geometric errors. The crystal clear optic (Fig. 3c) has a poorer surface finish from the cold cast process, showing a hazier image of the cell in the optic walls and suggesting it will have a lower optical efficiency and power output. The polycarbonate has a blue tinge to the material which would be perhaps aesthetically unpleasant in domestic applications.

The transmittance through a single CCPC optic made of each material has been calculated by comparing the results from Figs. 2a and 3f and displayed in Table 2 but this method (Fig. 1c) can only give the transmittance within the cell response range (300-1100nm) so the spectrophotometer was also used despite its inaccuracy (Fig. 1b) to gain indication of the wavelengths not absorbed by the cell (which would contribute to heating). As expected the glass optics give the highest transmittance over the widest wavelength range (Fig. 3e and f and Table 2). The crystal clear has the second greatest transmittance after the glass (Fig. 3e), and higher than the Topas material, but it covers a shorter wavelength range (400-1100nm) than desired for the silicon solar cells working range (Fig. 3f) giving it a lower effective transmittance for silicon cells as shown in Table 2. The Topas is the next highest

Table 2
Optical efficiency summary table.

	Av. Normal Incidence Transmittance (%) (Figs. 2a-3f)	Predicted Opt. Eff. (%) (Geometric Opt. Eff. x Transmittance)	Exp. System Opt. Eff.(Systemeff./cell eff.)
Method	EQE of cell with and without optics. (Averaged over 300-1100nm)	Monte-Carlo Ray Tracing gives 96% geometric optical efficiency for $n = 1.5$ [1,13,14].	I-V output from Solar Simulator of AM1.5G
Glass with AR	90.3	86.7	86.8
Uncoated Glass	89.7	86.1	83.7
Topas with AR	83.9	80.5	78.6
Uncoated Topas	83.9	80.5	76.0
Crystal Clear	77.0	73.9	70.7
Polycarbonate	74.0	71.0	72.4

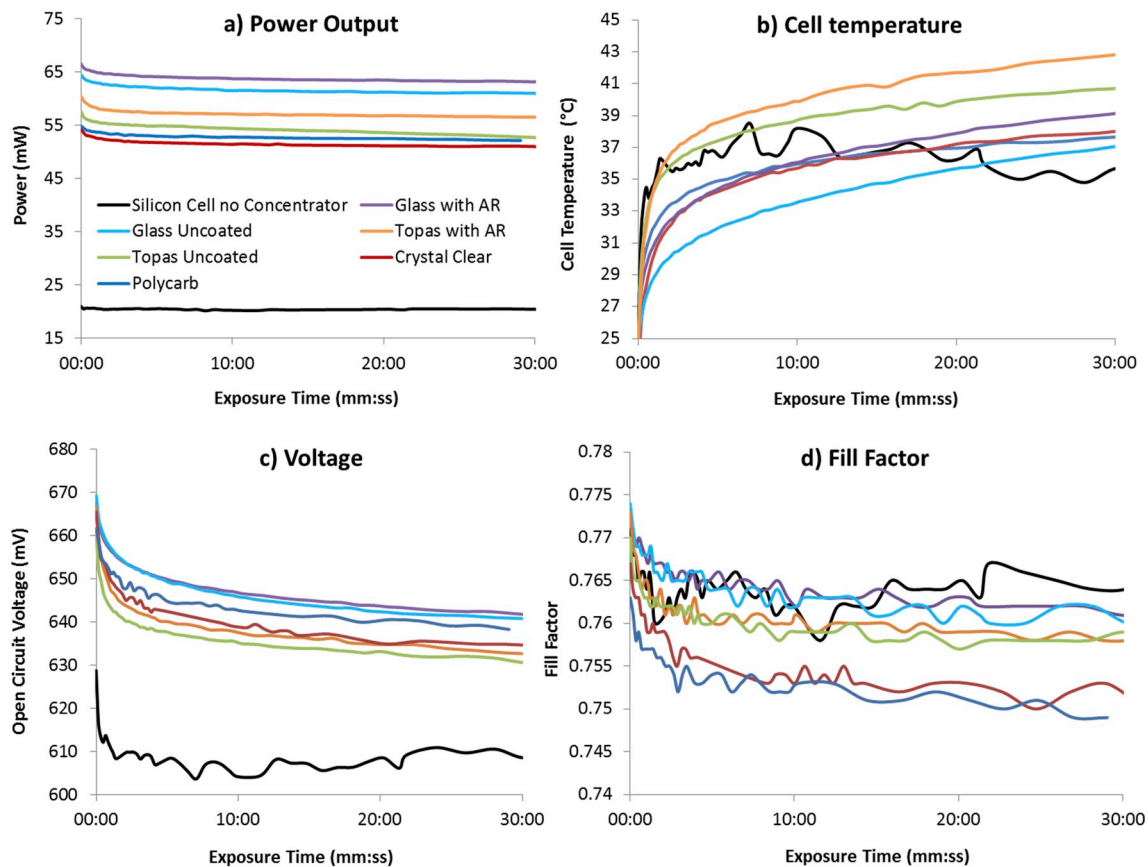


Fig. 4. a) Power of single unit prototypes during exposure to 1000W/m² AM1.5G light. b) Cell temperature relative to ambient temperature of the prototypes during light exposure. Corresponding open circuit voltage and fill factor of the prototypes also shown in c) and d).

transmitting material and covers a wider range of wavelengths and so is the second highest in Table 2. The polycarbonate is the poorest transmittance material in this application and study and due to its higher refractive index (Table 1) it is affected the most by the ‘incomplete exiting’ effect described previously and in Fig. 1b for the spectrophotometer, hence giving 74% transmittance in Table 2 despite Fig. 3b suggesting significantly lower. All the plastics transmit much less in the unusable IR wavelengths ($> 1100\text{nm}$) which could be beneficial to the lifetime of the solar cell.

To compliment the transmittance measurements, and investigate the effect of the material shrinkage effects during the moulding of the Topas and Polycarbonate optics (Fig. 3 b and d), the effective EQE of the cells, with the optics attached, was measured at normal incidence and also tilted incidence as shown in Fig. 3f and g respectively. At normal incidence, these EQE results take into account the optical absorption and entrance aperture reflectance losses. At an incidence angle of 30°, which is just within this CCPC's designed acceptance angle (35°) [13] the scattering losses (incomplete TIR and undesired reflection

angles) due to the surface roughness and shrinkage effects from manufacturing are incorporated (on entrance into the optic and during reflection at a side wall of the optic – Figs. 1a and 3g). The solar cells reflectance when receiving these angular incidence light rays is also in effect and all these factors contribute to the drop in output in Fig. 3g in comparison to Fig. 3f. All the optics outputs drop by ~8% but can be seen to be slightly more for the crystal clear optic, which becomes the second lowest performing device in figure g. This suggests the slope errors are stronger effect for the rougher cold cast crystal clear than the smooth but slightly shrunk injection moulded optics. The shrinkage flaws appear to have minimal effect on the optical efficiency at least in magnitude, the irradiance distribution may still be affected. Fig. 3e-g and Table 2 show very clearly and practically what wavelengths the solar cell can effectively utilise and what the best matching material is for the Silicon cell under study.

Overall, the injection moulded Topas optic is expected to give the highest power output after the glass. By comparing Fig. 3e-g and Table 2 it can be confirmed that the crystal clear, although has a high normal

incidence transmittance and no shrinkage effects, has a lower effective EQE at tilt than the Topas. This is because the surface roughness resultant from the cold cast moulding process causes more scattering loss when the light enters the optic and when it tries to reflect off an inner wall. The shrinkage effects of the Topas and Polycarbonate do not appear to have a significant effect on the optics performance when comparing Fig. 3f and g. The AR coated optics show only a very marginal increase in the transmittance and effective EQE due to these measurements being done with only a small normal incidence laser. Fresnel losses will be more significant when effective over the full aperture entrance of the optic.

4. Cell temperature, installation angle and performance

The single unit prototypes of silicon cells with different optics attached were tested under a solar simulator (Fig. 1d) of standard irradiance 1000W/m^2 AM1.5G and the cell temperature, ambient temperature (maintained at the standard 25°C) and I-V traces measured throughout the light exposure time. The results are shown in Fig. 4. As expected, the glass with AR coating produced the highest maximum power point, followed by the uncoated glass optic as shown in Fig. 4a. The Topas follows; the drops in power output corresponding to the higher absorption and possibly slightly lower quality optical finish. The AR coated optic again producing more power than the uncoated version. The Polycarbonate version then outperforms the crystal clear CCPC despite it having a lower transmittance (Fig. 3e-g) but as already discussed, the optical finish of the cold cast crystal clear is lower than any of the other optics and the polycarbonate has a higher refractive index (Table 1 and experimentally seen when comparing Table 2 transmittance values to Fig. 3e and the theory displayed in Fig. 1b). These results enforce the importance of not just a high performing material but also high quality manufacturing methods to match and take advantage of such material properties.

The temperature of the cells increases quickly within the first 5 min of light exposure before beginning to level off towards equilibrium, the plastic optics reaching equilibrium a little earlier than the glass optics due to the plastics lower thermal conductivity (Table 1). The silicon cell without a concentrating optic attached has a much more varying temperature as its not insulated (stabilised) from any small variations in air currents in its immediate surroundings. Interestingly the Silicon cell with no concentrator heats faster than the cells connected to glass optics, this could be due to the glass optics being naturally cooler initially and hence delaying the cells temperature increase until the glass has heated to room temperature, before which the glass optics almost act as a kind of heat sink for the cell. The temperatures of the cells with plastic optics attached to them are higher than their counterpart glass optics by $\sim 5^\circ\text{C}$ and of course increase quickly due to their higher absorption and lower thermal conductivity. The addition of AR coatings also noticeably increases the temperature of the cells (Fig. 4b) as it also increases the incident light upon the cell and the amount of power output generated (Fig. 4a), hence more resistive heating within the cell. The coating itself will increase the thermal insulation as it is an added material layer but due to its micrometer thickness, may be negligible in comparison to the increased power effects. It should also be noted that each of the cells will perform very slightly differently in terms of temperature coping and exact efficiency. The uncoated Topas prototype's power output decreased at a different rate in comparison to the other prototypes and similar the cell temperature continued to increase for longer before levelling off. This may be an inherent flaw in the cell which has caused it to heat up for longer despite receiving less input energy than its counterpart Topas with AR coating, which has the same thermal conductivity. The open circuit voltage of the uncoated Topas would also be expected to be above that of the AR coated Topas but again perhaps there are some internal localised cell flaws and resistances (not picked up by the thermocouple placed at the centre of the cell) which has caused the lower open circuit voltage despite not having the highest cell

temperature reading. The polycarbonate and crystal clear optics perform very similar in terms of power, cell temperature and fill factor due to their similar thermal conductivity values and optical efficiency. Their fill factors are the lowest in Fig. 4d which may be due to their poorer optical qualities which lead to not only lower optical efficiencies but also a different poorer quality irradiance distribution in comparison to the higher quality topas and glass optics. Again the open circuit voltage of the crystal clear and polycarbonate would be expected to be lower than the glass with AR coating in Fig. 4c due to Fig. 4b showing the AR glass to have a higher temperature towards the end of the exposure time. It could be these irradiance distributions, with perhaps higher concentration peaks upon the cell which cannot be picked up by the thermocouple in terms of temperature due to their locality and the resolution of temperature measurement required. There are other factors affecting the cell temperature and efficiency such as the increased concentration (this increases the open circuit voltage of the cell logarithmically [18,19,20]) and the different wavelength spectra incident on the cell (Fig. 3e). The glass optics will allow more infrared radiation to be absorbed by the cell and contribute to heating which is a different mechanism to the cell heating due to increased resistive losses from current increase. These factors are beyond the scope of this paper and as said the differences in the open circuit voltage could be a combination of all these small variations as well as the cells performance variance which is typically negligible for such scaled manufacturing.

The fill factors of Fig. 4d give confidence that there is not a large variability in optical efficiency between optics of similar material properties (e.g. Topas and Topas AR, Crystal Clear and PC, Glass and Glass AR). The irradiance distributions upon the cell must be similar for these grouped optics and hence their fill factors are also similar as seen by the grouping. If the shrinkage flaws in the moulded optics had a significant impact on the optics, then there would be more variability between the fill factors within these groups. Instead, they seem to follow similar variability to the two glass optics which do not have shrinkage flaws and so it can be assumed within their similar material groups that the irradiance distributions are of similar quality. The topas optics in particular are not far from matching the glass quality of optics.

The above results are all for horizontal devices with normal incident sunlight, which is the maximum temperature conditions. Flat or angled roof installations would however only have directly incidence solar radiation for a short period of time during solar noon depending on their location, where locations further from the equator would have lower sun angles even in mid-summer. Vertical window installations will however mean the insulating optics will only be at the side of the cell and no longer reducing the rate of convection directly above the cell. Measurements were hence taken of the Glass and Topas devices (both with AR coatings as these were the best performing devices from Fig. 4) orientated vertically and outside of the direct source of light but with a 45° mirror allowing normal incident light to be maintained on the devices (Fig. 5a). A test cell was used initially to calibrate this set up such that the light incident on the vertical devices was still 1000W/m^2 . In this way, the only variables altered between Figs. 4b and 5b measurements was the orientation of the devices and that Fig. 5b required the devices to be held in the air instead of upon a surface, which is the cause of 5b horizontal devices not demonstrating the exact same cell temperatures as in Fig. 4b. The power output, voltage and fill factor however was negligibly different between the two orientations and set ups.

From Fig. 5b it can be seen that the vertically positioned Topas devices have a lower cell operating temperature than when horizontal, which aligns with the theory that there is less insulating Topas material directly above the cell when vertical and hence more heat can be transferred upwards into the air instead of heating the cell. On the contrary, the Glass device has a higher cell operating temperature than when horizontal. This however can be explained by the way the cell is mounted on its small backing plate using sylgard (Figs. 1a, 3a and 5a). The sylgard adhesive has a thermal conductivity lower than glass

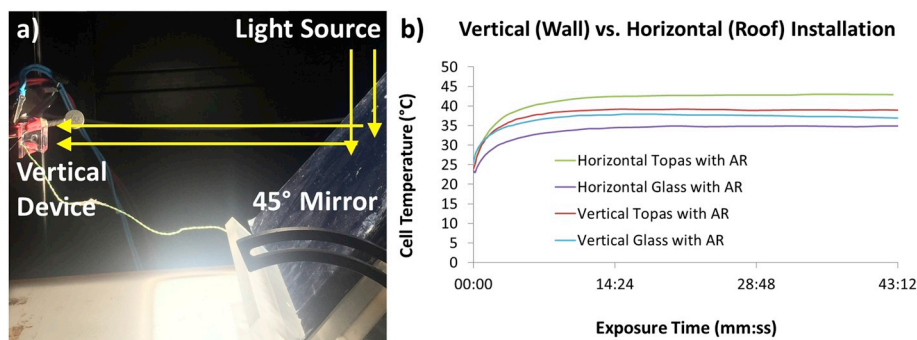


Fig. 5. a) Vertical set up of CCPC devices with normal incident light using angled mirror under light source. B) Cell temperature vs exposure time for two orientations of CCPC devices.

(Table 1) and although is a thin layer above the cell when the device is horizontal, is a substantially thicker layer above the cell when positioned vertically. This results in the vertical Topas and horizontal Glass having very similar cell operating temperatures despite their very different thermal conductivity for the optical materials. This is an important result as it shows that for vertical window installations (the main intention for these types of solar windows), the cell operating temperature will mainly depend on the adhesives used to secure the cell within the window and what inner medium the double glazing is filled with (e.g. air, vacuum or argon gas filled).

Further research into the different medium fillings associated with double glazed windows is required and how these will affect cell operating temperatures and efficiencies. The effects of different tilt orientations, for various facet architectures would be expected to lie between the two extreme orientations presented here but perhaps not linearly and will also vary with location, sun angle and typical weather forecast.

From these results it can be seen that high transmittance plastic optics which cover the full range of the solar cell such as Topas produce 11% less power than if Glass optics were used. However, the application of AR coatings (single layer magnesium fluoride) improves the optical efficiency and power output of Topas more than Glass (Fig. 6) and hence the gap between these materials power performance is reduced to 8%. The use of plastics does not increase the cell temperature significantly enough to be damaging although perhaps internal cell flaws (contributing to higher resistances) will be more noticeable as these will be affected more by the increased temperatures. The orientation of the proposed CPV embedded window will affect the cell temperature and can essentially negate the consideration of how thermally conductive the optical materials used are. For flat and angled roof installations the optic material will increase the cell temperature. For vertical window installations the encapsulate material and double glazing filling medium will increase the cell temperature.

There was no significant advantage seen from the lower infrared transmittance of the plastics on the solar cell over these exposure times

and results but they may have contributed to small alterations in the cell temperature and open circuit voltage. Further research into infrared filters are required to understand fully if they can increase the efficiency of silicon solar cells over much longer exposure times (months- years), such that they may have the potential of increasing their lifetime.

In terms of power to weight ratio, the main advantage of utilising the plastic optical materials, Fig. 6 shows the comparative results including that of a silicon cell mounted on its own with no concentrator optics.

Although the glass produced more power, the plastic optics, especially the Topas, produces the highest power to weight ratio, which is almost double that of glass (Fig. 6), especially if applying AR coatings to both types of optic. It should also be noted that the Topas optics would be expected to perform slightly better when the shrinkage flaws are fully eliminated with a more suitable manufacturing process involving a slower cool down period. It is perhaps this slight shrinkage on the top surface of the optic which results in the AR coating improving the Topas performance better than when applied to the glass (by 6% instead of 3%). It could also be argued that the surface roughness of plastic will typically always be less smooth than glass and hence should always benefit more from AR coatings than glass would.

The weight of these optics and similar concentrator photovoltaic systems may or may not be the highest priority depending on the application. Weight can limit the installation of a system on a roof or building façade in which case plastic may be the only option depending on regulations and infrastructure. Apart from that, the cost of transport and ease of installation will both be improved with reduced prototype weights but if space is a limiting factor and maximum power generation is required then glass optics will be the necessary choice. Most importantly, these results show the Topas devices have a higher power to weight ratio than even the original silicon cell without optics. This could suggest that plastic CPV panels would have higher power to weight ratios than even standard flat plate panels, which could lead to highly rewarding results in the applications of CPV technology. The

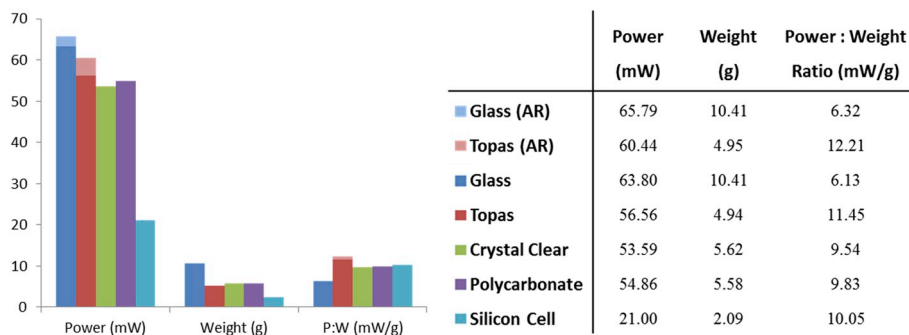


Fig. 6. Graph of Power to weight ratio of prototypes made from glass, Topas, Crystal Clear and Polycarbonate with data values given to the right.

experiments conducted here have effectively reversed the weight disadvantage of CPV technology due to the development and utilisation of plastic CPV optics.

5. Conclusion

Glass and varied plastic optics were compared for use in a low concentration photovoltaic device. Although the glass device showed a higher transmittance and power output, the plastic had a lower weight and hence a substantially greater power to weight ratio. The plastic optic caused a higher cell temperature by only 5° which was essentially eliminated when the devices were oriented vertically as in the case for vertical windows. Extended durability testing however is required to test the effects of UV discoloring in plastics, the lifetime of the cells under these slightly increased temperatures with IR filtering and the effects of vacuum sealed or argon gas pumped double glazing. For low concentration designs coupled with silicon cells for the application as double glazed window units where reduced weight is appealing, the plastic optics are an important alternative to glass. The plastic optics achieved double the power to weight ratio than the glass counterparts. Single layer antireflective coatings also proved to increase the power output by 3% for the glass optics and by 6% for the plastic Topas optics. Ultimately, it will depend on the cost of the materials, manufacturing scale and whether the weight or power is the priority factor which material should be used for low concentration optics. However, the weight disadvantage of CPV technology has not only been minimised through these experiments but reversed such that plastic CPV technology of this type could have higher power to weight ratios than even standard flat plate technology. This is a significant asset change for CPV technology and its applications. Further advantages of plastic optics for CPV may be found with the parallel development of 3rd generation solar cells and luminescent concentrators, both of which lend themselves to novel aesthetically pleasing and flexible designs for future building integrating CPV.

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